SOME OPERATIONAL ASPECTS OF INERTIAL SURVEYING SYSTEMS

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ABSTRACT

The surveying community has now accumulated about a decade of experience with the development, testing and operational use of inertial surveying systems. Tremendous progress has been made in identifying error sources and developing operational procedures to minimize or eliminate them, or devising means to correct for them. Even so, there remain three errors which are viewed as impediments to the efficient and effective application of inertial technology to precise surveying. The intent of this overview is to stimulate discussion and creative thought in order to hasten the development of some means of compensating for the underlying problems.

INTRODUCTION

Within the United States the Army and the Defense Mapping Agency (DMA) have been instrumental in bringing about the application of inertial technology to surveying and geodesy, having underwritten a large share of the developmental costs of the two systems manufactured in the United States (by Litton and Honeywell) which are now commercially available to the surveying industry and to the Mapping, Charting and Geodetic (MC&G) community.

A full decade of experience has also now been accumulated with comprehensive testing and operational use of the Litton Auto-Surveyor System (LASS), frequently referred to as IPS-1 (Inertial Positioning System One), the Rapid Geodetic Survey System (RGSS, a variant of the LASS/IPS-1), a prototype of the Honeywell GEO-SPIN system (IPS-2), the standard U.S. Army Position and Azimuth Determining System (PADS), and the latest arrival on the inertial surveying scene, the Litton Auto-Surveyor System II (LASS-II). A paper reporting on the results of operational testing of the two DMA-owned LASS-II units (IPS-3 and IPS-4) is presented at this symposium (PFEIFER & TYSZKA, 1985). DMA is, at the present time, funding the development of the second-generation Rapid Geodetic Survey System (RGSS-II, a variant of the LASS-II) under the technical leadership of the U. S. Army Engineer Topographic Laboratories (USAETL).

During this decade of experience, I consider the wholehearted cooperation of the world surveying community in seeking to make inertial systems more accurate to be the major factor in their success. If ever a system has been pulled into success, it is the inertial instrumentation. Countless effort has been expended in isolating error sources and in finding ways to either control the error propagation or to compensate for it. Without this worldwide effort, we would probably still be experimenting with a marginal piece of instrumentation.

During this period, the applications to which DMA has put the inertial surveying systems (ISS) have varied from a routine alternative to low-order conventional survey to the situation where the survey method was not a matter of choice, but it would have been completely impossible - or at least prohibitively expensive - to perform the survey by conventional means. The purpose of this paper is to highlight three operational aspects of inertial surveying systems which are regarded as major impediments to the efficient and effective use of these systems in precise surveying and geodesy. These are (1) heliborne operations, (2) heading sensitivity, and (3) eccentric occupation procedures. The intent is not to detract from the progress that has been made, but to stimulate discussion and creative thought, in order to accelerate the finding of solutions to the underlying problems.

HELIBORNE OPERATION

In order to produce results accurate enough for use in surveying and geodesy, the characteristic drift of an inertial platform must be controlled. The inertial surveying systems accomplish this by performing a zero-velocity update (ZUPT)) at frequent intervals, typically every three to five minutes, depending on the survey type and the desired accuracy. At these updates, any accumulated errors in the integration of the sensed accelerations are manifested as velocity anomalies, and are set to zero. To accomplish this, the system must come to a complete stop (and remain at rest for 20 to 60 seconds, depending on environmental conditions such as wind gusts and/or the self-induced vibrations of the transporting vehicle). This must take place every three to five minutes along the survey traverse. Accordingly, the mode of travel is limited to a ground vehicle or a helicopter.

Heliborne operation is more costly per hour, but also more productive, and is to be preferred for large-scale survey projects. As a matter of fact, in areas not served by an adequate road network, there is no choice -- the helicopter is the only practical means of conducting the survey. Unlike the land vehicle, which is severely constrained by trafficability considerations, the helicopter traverse can be designed to consist of straight courses confined to narrow corridors, and can be covered in less time.

Both these aspects of heliborne operation -- ability to follow a narrow corridor and faster rate of progress -- are advantages over land-vehicle operation from the point of view of ISS error propagation. It would seem, therefore, that the heliborne inertial surveys should be not only more productive, but also more accurate. Such is not the case, unfortunately. The results of heliborne inertial surveys are consistently less accurate (by a factor of two or three) than those obtained when the land vehicle is used as the mode of travel. This is attested to by larger misclosures at control points and larger disagreements (splits) at crossover points. Similar accuracy degradation of heliborne ISS surveys has been reported by others, e.g. CROSS & WEBB (1980).

The factors causing this performance degradation are not yet well known. Because of economic considerations, most testing of the inertial surveying systems has been carried out in a land vehicle, while most production has been done with the helicopter -- by the Defense Mapping Agency as well as by others. Some likely causes which are speculated upon in the literature are (1) much more severe vibration environment which degrades overall ISS performance, (2) marginal ZUPTs because of vibration and greater susceptibility to wind-induced motion while on the ground, (3) more cumbersome and hence less accurate offset measurements which, nonetheless, are required more often because of greater difficulty in positioning the ISS "lever arm" reference mark accurately over the desired ground point, and (4) the helicopter's tendency to accelerate at takeoff in a markedly nose-down attitude which induces, as a consequence of a large pitch angle displacement, an effect analogous to heading sensitivity, to be discussed next.

HEADING SENSITIVITY

As already mentioned, it is a characteristic property of inertial systems that they drift. This drift can be observed as gradual changes of the output coordinates when the system is at rest. A great deal of engineering and precision manufacturing effort has gone into the best attempts at minimizing this effect; indeed, the quality of an inertial system is implicitly given by its drift per unit of time. Since this drift cannot be eliminated altogether, the next best thing is that it be linear, so that it can be evaluated and compensated for in the data processing stream.

Heading sensitivity is the name given to the observed phenomenon of a change in the system's drift which is introduced, in an unpredictable manner, by a significant change in the direction of travel. The resulting nonlinear drift is not adequately compensated by either real-time Kalman filtering or after-the-fact smoothing. As a consequence, the accuracy of the results suffers significantly when the inertial traverse deviates from a straight-line path. To paraphrase HARRIS (1977), the ISS produces excellent results for a straight-line traverse; however, the results are severely degraded otherwise. Where a straight-line traverse might yield an accuracy of 20 or 30 centimeters, if the same distance is made into an L-shaped traverse, the error may become several meters.

All inertial surveying systems exhibit heading sensitivity to a degree, the Litton systems perhaps more than the others (SCHWARZ & GONTHIER, 1981). The causative factors, again, are not yet sufficiently well understood. SCHWARZ & GONTHIER (1981) have shown that a significant improvement could be attained by changing the Litton real-time Kalman filtering and/or after-the-fact smoothing algorithms. BROXMEYER (1964, p. 45) points out that gyro drift is to some extent dependent on the orientation of the gyro case with respect to the specific force vector, i.e., of the stable element with respect to the direction of acceleration. This, however, is discounted by some experts as, at most, a second-order effect.

The conventional wisdom is that the heading sensitivity is caused mainly by thermal gradients inside the inertial measurement unit (IMU) case, created by the necessary temperature control of the IMU, and/or by magnetic forces resulting from the interaction of electromagnetic fields generated by the inertial platform devices and the associated electronic control circuitry. One approach to solving this problem, which is now in the discussion stage, is to mount the IMU in a set of external gimbals, so that the IMU case, as well as the stable element, is maintained (approximately) level and oriented to north (local-level systems), or in a fixed orientation in space (space-stable systems).

ECCENTRIC OCCUPATION PROCEDURE

With one notable exception (Honeywell GEO-SPIN), the inertial surveying systems now in use lack an integral, convenient device with which rapid and accurate survey ties to ground points a short distance away can be made. This is a serious drawback from the point of view of both productivity and accuracy. The standard procedure, with the Litton systems, is to have a reference mark in a convenient location (such as the door frame on the driver's side in the case of a land vehicle, or the landing sled strut on the pilot's side in the case of a helicopter). The coordinates of this reference mark are established with respect to the center of the IMU by careful measurement, to establish the "lever arm" between the IMU and the mark. The inertial survey is then planned so that the vehicle or helicopter reference mark can be positioned directly over the desired ground point. Vertical distance from the ground point to the reference mark is measured (with a long ruler) and manually entered with other necessary data via the control/display unit (CDU) keyboard, which comprises the "mark" or "update" procedure. Even though the magnitude and direction of the "lever arm" from the center of the IMU is accurately determined, the difficulty of positioning the vehicle, and especially a helicopter, precisely over the desired ground points need not be belabored. The resultant inaccuracies feed directly into the survey results.

The next step up in sophistication is to install a draftsman's protractor at the reference mark, with a hook at its center where a measuring tape can be attached. The real-time software has been modified to accept (via the CDU keyboard) the protractor angle, horizontal distance measured from the reference mark to the ground point, and vertical distance measured with a long ruler from the ground point to the horizontally held measuring tape. Aside from being cumbersome, this procedure is also not very accurate, and certainly not worthy of a sophisticated piece of high-technology equipment having up to a half million dollar price tag (WATERHOUSE, 1985). Since the resolution of the ISS is typically three centimeters in the horizontal coordinates and one centimeter in the vertical coordinate, such crude procedure is marginally adequate for offsets of a few feet; it is patently inadequate and impractical for offsets across a six-lane highway. RUEGER (1984, 1985) treats this problem in detail, giving a comprehensive error analysis of this procedure, as well as that of the proposed alternative.

To be sure, provision for accurate determination of eccentric occupation has been designed into the Litton systems, in the form of a Porro prism attached to the IMU case, by means of which the ISS-determined azimuth can be optically acquired and transferred. The associated procedure calls for (1) the setting up of a theodolite (or total station) over the desired ground point; (2) jockeying of the vehicle (or helicopter) to bring the Porro prism into alignment with the optical axis of the theodolite; (3) measurement of the slant distance between the theodolite and the Porro prism, the corresponding zenith angle, and the height of the theodolite above the ground point; and (4) manual entry of these measured values via the CDU keyboard. Needless to say, this procedure is not used by anyone, to our knowledge, in production work.

One practical solution to this problem, worked out in detail by RUEGER (1985), is the addition of a total station to the system, physically attached to the ISS, aligned with the IMU coordinate system, and its digital output integrated with the system's data processing stream. Unfortunately, the currently available total stations, designed for conventional surveying, are too sophisticated and an overkill in terms of both accuracy and cost for the application at hand. It remains to be seen whether one can be found that is sufficiently rugged to survive the shocks and vibration to which hard-mounted equipment is subjected in a land vehicle and/or helicopter. Also, the manufacturer's interest and assistance must be sought to provide the necessary optical alignment aids, the electronic data interface with the system's computer, and the associated modification of the real-time software.

CONCLUSION

The foregoing discussion of three operational aspects of inertial surveying systems -- heliborne operations, heading sensitivity, and eccentric occupation procedures -- is certainly not exhaustive. It merely brings up the three problems I perceive as being dominant, and in need of a solution, and which adversely affect the efficiency and effectiveness of inertial surveying systems today. Neither is this discussion meant as a criticism of the instrumentation which has been developed. These systems, by and large, perform well and live up to specifications. Nevertheless, these problems must be resolved if the objectives of present research-and-development efforts, such as the interpolation of the components of the gravity vector with usable geodetic accuracies, are to be successfully achieved.

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